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Environmental diagnosis and planning actions for municipal waste landfills in Estado Lara (Venezuela)

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Abstract

Municipal waste production in Venezuela and the other Latin American and Caribbean countries continues to increase substantially. Given that uncontrolled management of waste in landfills leads to negative environmental impacts, there is a need to undertake an environmental diagnosis of existing facilities in order to analyse the problems they present and take the necessary measures for reducing adverse effects. The objective of this paper is to study the possibility of applying an environmental diagnosis methodology developed by the University of Granada in order to quantify the environmental impact of urban waste landfills. Seven deposit points located in Estado Lara (Venezuela) were studied. Some modifications in the methodology were introduced to take into account urban waste characteristics and the legal framework in Venezuela. Application of the methodology obtained a series of environmental indexes, making it possible to quantify the impact of the deposit points on the following environmental elements: surface water, groundwater, atmosphere, soil and human health. The indexes were denominated as follows: Environmental Landfill Interaction Index; Environmental Risk Index; Environmental Value and Probability of Contamination. Analysis of results showed significant operation and design problems in all the landfills. The study also made it possible to compile a catalogue of all the deposit points and draw up a list of priorities for action. In the case of Pavía, a Conditioning Plan is required to improve operation and

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design. In the remaining six deposit points, each index needs to be studied carefully to determine if a Conditioning Plan is sufficient, or if a Sealing and Closing Plan is required owing to the unsuitable location of the deposit points.

Keywords: Municipal solid waste; Landfill; Environmental impact assessment; Landfill capping; Landfill design; Landfill recovery

Contents

1. Introduction

In developing countries, natural urban population growth and immigration from rural areas are contributing to a substantial increase in urbanization levels. Latin America and the Caribbean represent the most built-up regions, with three quarters of the population living in urban areas characterized by high-population density, high consumption of energy, water and food and significant environmental impacts. Five of the 30 most populated cities in the world are in Latin America: Sao Paulo (16.4 million), Mexico City (15.6), Buenos Aires (12), Río de Janeiro (9.9) and Lima (7.5) [1].

In the period 1970–2000, the urban population increased from 158.6 to 383 million people, while urban development increased from 57.4% to 75.3%. At the beginning of the 21st century, 79.8% of the South American population live in urban areas; in Central America and the Caribbean the urban population represents 67.3% and 63%, respectively. Although there are important differences in urbanization levels in each region, it is predicted that the urban population will reach 526 million people by 2020 (80.4%) [2,3].

Urban waste management in Latin America and the Caribbean has evolved in response to urbanization, economic growth and industrialization [4]. In 1995, the regional urban population generated approximately 330,000 tonnes of urban waste per day; one fifth of this quantity was generated in the three biggest cities: Mexico City, Sao Paulo and Buenos Aires [5,6].

Municipal waste problems are caused both by the quantity of waste generated, which have doubled in the last 30 yr from 0.2–0.5 to 0.5–1.2 kg per inhabitant per day, and its composition. While the percentage of organic matter in municipal waste has fallen, the percentage of voluminous and non-biodegradable components such as plastic, metals and glass, etc. has increased. Table 1 shows waste production in several Latin American and Caribbean cities.

The absence of a modern and practical policy for solid waste management constitutes one of the weakest points in the system [4]. Although the percentage of waste collection is high (nearly 90%), inappropriate treatment and final disposal are the most frequent solutions. Negative impacts are caused by the inappropriate location and operation of the landfills, while there is a widespread practice of people recovering waste in insanitary conditions [3,6,7].

Open-air waste burning, open-pit dumping and uncontrolled waste disposal in landfills can result in negative impacts to public health and to the environment [4,8,9], and may also lead to undesirable social and environmental effects [10]. Additional negative impacts include potential health hazards, including fires and explosions [11,12], vegetation damage [13] unpleasant odours [14], landfill settlement [15], ground and surface water pollution [16,17], air pollution [18] and global warming [19,20]. Approximately 43% of generated waste is finally disposed by open-dumping [21]. Although legal provision exists in some countries, there are usually insufficient human resources and physical infrastructure to implement it.

1.1. Municipal waste management in Venezuela

Only a small number of studies to determine municipal waste composition and characterization have been carried out in Venezuela. Sánchez [22] compiled a study of municipal waste and proposed that the extent of the waste generation task depended on population size; if the population was less than 25,000 inhabitants, the generation task would vary between 0.3 and 0.65 kg per inhabitant per day; for 25,000–50,000 inhabitants the task increased to 0.29–0.75 kg per inhabitant per day; figures for larger populations were as follows: 50,000–100,000:0.6–1.1 kg per inhabitant per day; 100,000–500,000:0.6–1.15 kg per inhabitant per day; over 500,000:1.2 kg per inhabitant per day [21].

Municipal waste management in Venezuela has been based on a simple system comprising the following stages: generation, collection and final disposal under partially controlled or uncontrolled conditions. The context in which municipal waste management, control and actions have been carried out has been marked by inappropriate planning, insufficient budget, out-of-date figures, inadequate technical and professional capacity and absence of environmental control [23].

The Municipal Waste Sector Analysis in Venezuela [5] reveals difficulties resulting from the location of waste disposal sites near to areas of dense population. In 2000, detailed accounts of 215 deposit points in Venezuela were compiled; 147 were shown to

Table 1
Urban waste generation in Latin American and Caribbean cities

City	Population (millions of people)	Urban waste production	
		tn/day	Kg/inhabitant day
South America			
Lima	7.5	4200	0.56
Buenos Aires	12	10,500	0.875
Sao Paulo	16.4	22,100	1.348
Río de Janeiro	9.9	9900	1.00
Santiago	5.3	4600	0.868
Bogotá	5.6	4200	0.75
Medellín	1.5	750	0.5
Barranquilla	1	900	0.90
Cali	1.8	1350	0.75
Cartagena	0.6	560	0.933
Montevideo	1.4	1260	0.90
Quito	1.3	900	0.692
Caracas	3	3500	1.167
Asunción	1.2	1100	0.917
La Paz	0.7	380	0.543
Salvador	2.8	2800	1.00
Curitiba	2.1	1300	0.619
Brasilia	1.8	1600	0.889
Belo Horizonte	3.9	3200	0.821
Joao Pessoa	0.7	250	0.357
Rosario	1.1	700	0.636
Central America			
Mexico	15.6	18,700	1.199
Monterrey	2.8	3000	1.071
Managua	1	600	0.600
Guatemala	1.3	1200	0.923
Tegucigalpa	1	650	0.650
San José	1	960	0.960
Panama	0.8	770	0.963
San Salvador	1.3	700	0.538
Caribbean			
La Habana	2	1400	0.7
Santo Domingo	2.8	1700	0.607
Puerto España	0.5	600	1.200

operate in totally uncontrolled conditions; 50 were uncontrolled but located in suitable sites, although operating conditions were inappropriate; 17 were partially controlled landfills and only one operated in an appropriate location and under suitable conditions.

In spite of this, Venezuela has a legal framework related to urban waste management. The principal laws in this regard are *La ley de Residuos and Desechos Sólidos*[1] [24] and

[1]Law of Solid Waste.

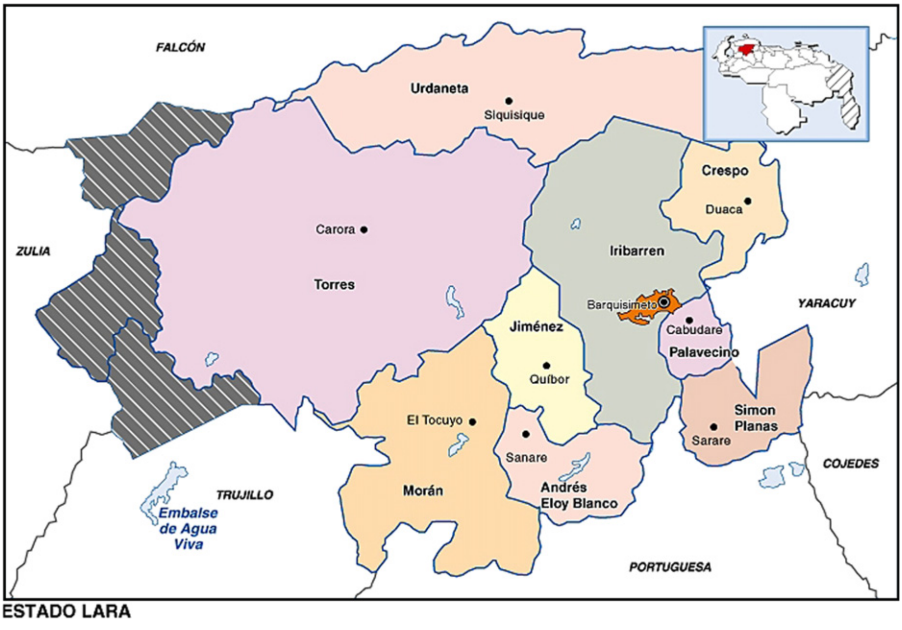


Fig. 1. Location of study area and administrative region.

La Resolución 230 relativa a las Normas Sanitarias para el proyecto y operación de un relleno Sanitario de residuos sólidos de índole atóxica[2] [25] which constitute the tools to achieve overall sustainable waste management in order to protect health and the environment.

Further studies in the country have described problems relating to inappropriate location of deposit points, unsuitable operation conditions, disregard of the legal framework [23,26,27] and the presence of people recovering waste in the deposit points [28]. However, these negative impacts have not been quantified.

The present paper describes an environmental diagnosis methodology for municipal waste, developed in the University of Granada (Spain) and applied to Estado Lara (Venezuela), in order to determine the negative impacts resulting from landfills operating in this area.

1.2. Study area: Estado Lara (Venezuela)

Estado Lara is located in the central western region of Venezuela. It borders on Estado Falcón to the north, Estado Trujillo and Portuguesa to the south, Estado Yaracuy and Cojedes to the east and Estado Zulia to the west. The area of study comprises nine provinces, with a surface area of 19,800 km^2 (Fig. 1).

[2]Resolution 230 of 10/10/90 governing Sanitary Norms for design and operation of sanitary landfills for atoxic solid wastes.

2. Methodology for environmental diagnosis of landfills

2.1. General aspects related to methodology application

The methodology developed by the University of Granada is designed to quantify the impacts of municipal waste landfills, taking into account the characteristics of the area in which the landfill is located, as well as the mass of waste [9]. The methodology obtains a series of environmental indexes which quantify the environmental interaction between the deposit point location and the environmental value of the following potentially affected elements: surface and ground water, atmosphere, soil and human health. In addition, the methodology assesses the operational state of the landfill from the environmental point of view [29].

The environmental indexes are denominated as follows: the Environmental Landfill Interaction Index (ELI), the Environmental Risk Index for each environmental element (ERI_i), the Probability of Contamination for each environmental element (Pbc_j) and finally Environmental Value (eV_i) for each environmental element. Expressions (1), (2) and (3) are used to calculate the environmental indexes [9,29]. In expression (3), C_j is the classification of the variable and W_j is its weighting.

$$\mathrm{ELI} = \sum_{i=1}^{5} \mathrm{ERI}_i, \tag{1}$$

$$\mathrm{ERI}_i = \mathrm{Pbc}_i \times \mathrm{eV}_i, \tag{2}$$

$$\mathrm{Pbc}_i = \frac{\sum_{j=1}^{n} C_j \times W_j - \sum_{j=1}^{n} \left(C_j \times W_j\right)_{\min}}{\sum_{j=1}^{n} \left(C_j \times W_j\right)_{\max} - \sum_{j=1}^{n} \left(C_j \times W_j\right)_{\min}}. \tag{3}$$

By definition, the methodology should be applied to urban waste landfills only. The landfill waste composition may be obtained from existing historical data, data on waste in population centres or from on-site characterization [4,9,29].

2.2. Modifications to the methodology

For each environmental element, Calvo et al. [4,29] formulated a further index denominated weighting coefficients (EWC_i). This type of coefficient was formulated to relate indicators of the landfill impact with the spatial, temporal and legislative characteristics of each environmental element [30,31]. At the time, inclusion of this coefficient represented a technical–political–social decision regarding the relative importance of factors such as public health, landfill settlement, and groundwater protection, by prioritizing them within a common framework. However, application of the coefficient in different countries generated equal values for all the areas under study, and thus did not provide a basis for the comparison of landfills [4,9]. Consequently, it was decided to exclude this coefficient in later studies [32]. Classifications for the indexes used are shown in Table 2.

Table 2
Classification of different indexes [29]

Low	Average	High
$0 \leqslant ELI < 5$	$5 \leqslant ELI < 10$	$10 \leqslant ELI \leqslant 15$
$0 \leqslant ERI_i < 1$	$1 \leqslant ERI_i < 2$	$2 \leqslant ERI_i \leqslant 3$
$0 \leqslant eV_i < 1$	$1 \leqslant eV_i < 2$	$2 \leqslant eV_i \leqslant 3$
$0 \leqslant Pbc_i < 0.3$	$0.3 \leqslant Pbc_i < 0.6$	$0.6 \leqslant Pbc_i \leqslant 1$
$0 \leqslant Pbc\text{-}s_i < 0.3$	$0.3 \leqslant Pbc\text{-}s_i < 0.6$	$0.6 \leqslant Pbc\text{-}s_i \leqslant 1$
$0 \leqslant Pbc\text{-}o_i < 0.3$	$0.3 \leqslant Pbc\text{-}o_i < 0.6$	$0.6 \leqslant Pbc\text{-}o_i \leqslant 1$

Further changes in the methodology were introduced to take into account of the Venezuelan legal framework and the methodology used in certain previous studies:

- In consideration of Resolution 230 concerning Sanitary Norms for the Design and Operation of Sanitary Landfills for A-toxic Solid Wastes, changes were made to the following variables: compaction, covering material, final coverage and landfill operation capacity.
- While Calvo et al. [9] applied DRASTIC methodology to classify the variable 'aquiferous characteristics', studies in Venuezuela have used GOD methodology [32,33]. It was decided to use the GOD methodology in the present study, since data necessary for DRASTIC proved difficult to obtain.
- In view of the composition of Venezuelan waste, it was necessary to change the variables 'landfill age' and 'organic matter composition' of the environmental element 'soil'.
- The variable 'distance from population centre' for the environmental element 'human health' was also changed to take into account legislation from Venezuela [24,25].

2.3. Data acquisition

Application of the methodology is based on the collection of data relating to the physical environment, state and characteristics of deposit points. Data collection involved visiting the different deposit points as well as studying existing information regarding the points and characteristics of their environment.

For this process, standardized checklists were designed to ensure comprehensive data acquisition. Two models were used: one to record the environmental characteristics and the other to obtain relevant information regarding the physical medium characteristics of the deposit point location. The first checklist included data such as geology, geomorphology, topography, surface water, groundwater, climate, soil uses, flora and fauna, while the second compiled information on waste composition, treatment, presence of special waste, leachates, unauthorized persons, animals, lack of fences, exposed waste, lack of covering material and surface drainage.

In total, seven operational municipal waste landfills were studied: Pavia (community of Barquisimeto), Los Jebes (community of Quibor), Los Palmares (Tocuyo), Curva del

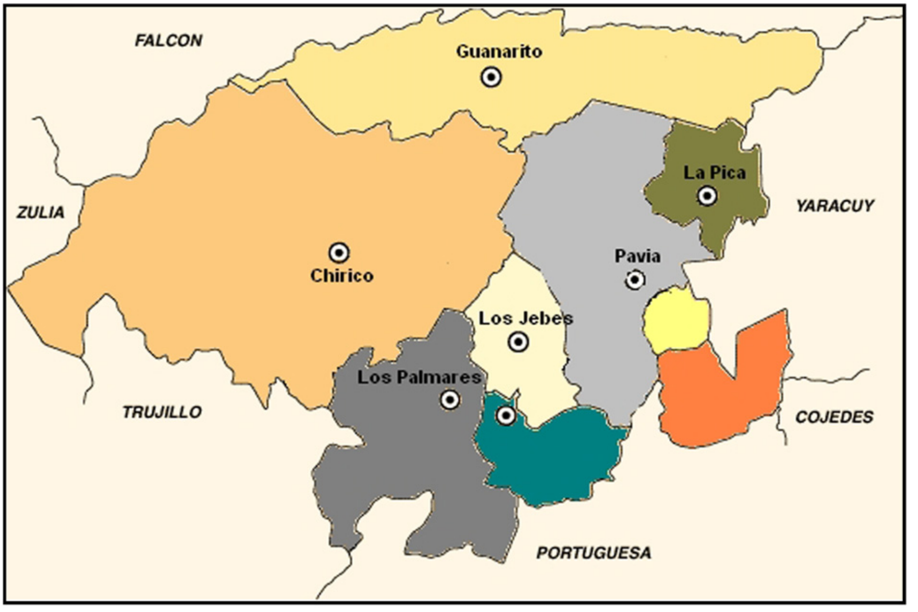


Fig. 2. Location of deposit points.

Viento (Sanare), Chirico (Carora), Guanarito (Siquisique) and La Pica (Duaca). Fig. 2 shows the location of the deposit points included in the study.

2.4. *Statistical analysis*

Data obtained in the study were analysed by computer-assisted statistics, using SPSS for Windows 11.5.1 (Standard Version; SPSS Inc. 1989–2002). The arithmetic mean was used to determine which environmental elements were most affected as a consequence of the landfills. The least significant differences test (LSD-test) was used to measure the differences between the impact of the various deposit points and to determine which environmental elements were most affected. An analysis of variance test (ANOVA) was applied to assess the homogeneity of variance, with a significance level of 5% ($p<0.05$). Schetfe's test was used for multiple comparisons and to obtain a homogeneous group.

3. Methodology application

3.1. *Description of the deposit points*

The results of the data acquisition checklists for each deposit point are summarized in Tables 3–6.

3.1.1. *Environmental indexes*

As indicated above (2.1), results obtained from the environmental diagnosis methodology for each deposit point were studied in relation to the following

Table 3
Description of Pavía and Los Jebes deposit points

Name	Pavía	Los Jebes
Landfill surface area	4 ha	4 ha
Composition of disposed waste	Mainly organic matter	Organic material, paper, cardboard, glass and plastic
Geology	Soil characterized by sequence of rock types including lutite, marga, ftanite and caliza limestone, presenting bright colours on the surface. Many seams consist of philitic rock, with shiny sericritic surfaces	Soil covered by sediments deriving from quaternary-age rivers and lakes. Characterized by lenticular sand and gravel with interseams of clay. Soil matter predominantly fine
Geomorphology	Moderate slopes, 2% approx.	Gentle slopes from south to north, between 0.6% and 2%
Surface hydrology	No water bodies in surrounding area. An intermittent ravine crosses the entrance of the landfill. Drainage takes place from east to west, passing downstream to form an affluent of the ravine known as La Ruazga	No water bodies or ravines in surrounding area. Drainage occurs from east to west, towards the ravine known as Los Barrancos, an affluent of the stream Las Raíces, which is in turn an affluent of the river Tocuyo
Ground hydrology	Local discontinuous aquifer. No record of drilled wells in the area	Presence of major aquifer deriving from ancient subterranean lake eliminated by sedimentation. Permeable material of aquifer composed of clay and silt with interseams of sand, gravel and rock mass interconnected at irregular intervals
Seismic risk	Average acceleration: 270 gal (excedence probability 15%)	Average acceleration: 316 gal (excedence probability 15%)
Climate	Semi-arid, temperate to hot. Average annual precipitation: 645 mm approx; average annual temperature: 24.5 °C; average annual evaporation: 2250–2330 mm	Arid and temperate. Average annual precipitation: 500 mm approx; average annual temperature: 20–32 °C; average annual evaporation: 2329 mm
Flora and Fauna	Shrub-like vegetation adapted to arid climates, characterized by fleshy or woody thorned species such as thistles and spiked grasses. Birds mostly granivorous or predators of insects and reptiles. Presence of frugal mammals, especially rabbit and fox. Terrestial reptiles belong to the lacertilian group, e.g. lizard and iguana, or to the ophidian group, e.g. the rattlesnake (genus *Crotalus*) and coral snake (genus *Micrurus*)	Predominance of vegetation adapted to arid climates and resistant to drought, including cacti and stiff-leaved plants of the genus *Bromeliaceae*. Presence of herbaceous grasses and sedges. Birds mostly granivorous or predators of insects and reptiles. Presence of frugal mammals, especially rabbit and fox. Terrestial reptiles belong to the lacertilian group, e.g. lizard and iguana, or to the ophidian group, e.g. the rattlesnake (genus *Crotalus*) and coral snake (genus *Micrurus*)

Table 3 (*continued*)

Name	Pavía	Los Jebes
Soil uses	Urban and residential	Agricultural
Infrastructure	Landfill located at 0.05 km from the 001 artery road and at 2 km from the Moyetones Distribution Centre (North ring-road) and Avenida de las Industrias. Jacinto Lara International Airport situated at 6.5 km	Landfill located at 1 km from the 007 artery road and at 0.01 km from secondary road network. A bridge is situated at 1.1 km. High-voltage cable network and water supply system both situated at 1 km
Distance from population points	Neighbourhood known as Pavía Abajo situated at little more than 1 km; Rafael Caldera neighbourhood (pertaining to Barquisimeto) at 4 km	Quibor situated at 2 km

Table 4
Description of Los Palmares and Curva del Viento deposit points

Name	Los Palmares	Curva del Viento
Landfill surface area	4 ha	1.5 ha
Composition of disposed waste	Organic material, paper, cardboard, glass, metals and to a lesser extent, plastic	Organic material, paper, cardboard, glass, metals and to a lesser extent, plastic and textiles
Geology	Soil characterized by a sequence of lutite and arenaceous rock types, with some lenticular limestone. The arenaceous rock presents characteristics similar to hard rock, forming profiles with monoclinal crests or incipient secondary crests within the landfill. The softer lutite rock is easily undermined and carried away by surface run-off	75% of soil formed by laminar grey lutite, with occasional thin layers of limolite, lenticular limestone—at times fossiliferous—and arenaceous rock, more frequent towards the upper part. The lutite rock of the river Tocuyo presents fossils of benthic foraminifers
Geomorphology	Largely homogenous flat topography with one slope ranging from east to west, less than 2%	Ondulating topography with accentuated peaks. Predominance of slopes of over 15%
Surface hydrology	No water bodies in surrounding area. A ravine known as Honda is situated at 1.25 km and the river Tocuyo at 3 km. Presence of drainage courses near the landfill, deriving from processes of erosion	No water bodies in surrounding area. Landfill situated 0.5 km upstream from hydrological network formed by the intermittent ravine known as los Naranjos, which is an affluent of the Botucal ravine. Also situated at 0.5 km upstream from the ravine known as Las Rositas, affluent of the Acarigua ravine
Ground hydrology	Local discontinuous aquifers. Presence of sedimentary and metamorphic rock indicates soil of very low to average permeability	No available data on groundwater, although locality classified as 'poor' with regard to potential existence of aquifers

Table 4 (*continued*)

Name	Los Palmares	Curva del Viento
Seismic risk	Average acceleration: 345 gal (excedence probability 15%)	Average acceleration: 346 gal (excedence probability 15%)
Climate	Semi-arid, temperate. Average annual precipitation: 607 mm; average annual temperature: 27 °C approx.; average annual evaporation: 2249 mm approx.	Sub-humid to dry, cold. Average annual precipitation: 878 mm; average annual temperature: 22 °C
Flora and Fauna	Predominance of vegetation adapted to arid climates, such as spiked grasses, shrub-like bushes and weeds. Most representative species include *Cestrum Nocturnum* and plants of the genus *Lemaireocereus griseus*. Birds mostly granivorous or predators of insects and reptiles. Presence of frugal mammals, especially rabbit and fox. Terrestial reptiles belong to the lacertilian group, e.g. lizard and iguana, or to the ophidian group, e.g. the rattlesnake (genus *Crotalus*) and coral snake (genus *Micrurus*)	Vegetation largely characteristic of wooded foothills: thickets, spiked grasses and weeds. Birds may be granivorous, herbivorous or predators of insects. In sheltered areas mammals include tapirs and bats, while in the open spaces nocturnal or crepuscular herbivores are present, such as the tailless rodent *paca*. Evidence of small and medium-sized predatory mammals
Soil uses	Urban	Uncultivated
Infrastructure	Landfill situated at 1 km from the 007 artery road and at 0.8 km from secondary road network. A bridge is situated at 0.8 km. Electric cables pass overhead. At approximately 1 km there are water storage tanks used for urban water supply	Landfill situated at 0.1 km from secondary road network
Distance from population points	Built-up area at approximately 0.8 km	Palo Verde and Sanare situated at 1.5 and 2.5 km, respectively

environmental indexes: Environmental–Landfill Interaction Index, Environmental Risk Index, Environmental Value and Probability of Contamination.

3.1.2. Environmental– landfill interaction index

Table 7 shows different ELI values for each deposit point studied, while statistical data for this Index are shown in Table 8. The mean value for ELI in the study area was 6.13, with a maximum value of 7.67 for the landfill known as La Pica, which presents the greatest environmental impact in Estado Lara. A minimum value of 3.74 was presented by the landfill Pavia, corresponding to the lowest environmental impact. In all cases, values obtained by the ELI index indicate a classification of the environmental impact as average, except Pavia where the classification is low (Table 7).

These different indexes allow us to establish priorities and to plan the order of actions to be carried out on the landfills. Landfill La Pica shows the highest environmental impact and there is consequently a higher priority to undertake environmental action on this landfill. Table 7 shows priorities for landfills in the study area.

3.1.3. Environmental risk index

Fig. 3 shows the Environmental Risk Index for different environmental elements in the seven deposit points. The mean value for ERI_i in the study area was 1.23 (Table 8). The maximum value (2.58) corresponded to Los Palmares (3), relating to the environmental element 'human health'. The minimum value obtained (0.00) corresponded to Pavia (1) and Curva del Viento (4), both for groundwater.

Table 5
Description of Guanarito and Chirico deposit points

Name	Guanarito	Chirico
Landfill surface area	1.5 ha	6 ha
Composition of disposed waste	Organic material, paper, cardboard, glass, plastic and textiles to a lesser extent	Mainly organic materials, paper and cardboard. Glass and plastic to a lesser extent
Geology	Soil characterized by heterogeneous mix of sands, clay, silt and blocks of diverse sizes	Lithology mainly characterized by lutite rock, also arenaceous rock and limestone. Many examples of 'Colon formation', typified by dark grey or black microfossiliferous lutite and pyritic rock masses. The lutites present greater degree of sand content towards the base. Likewise many examples of 'Moon formation', typified by laminas of dense limestone, dark grey to black in colour, carbonaceous or bituminous in content and a few centimeters in width; black clays, at times calcareous; ellipsoidal and disk-like masses of hard black limestone, varying in dimension from a few centimetres to almost one metre, and black ftanite rock
Geomorphology	Presence of slopes varying from 1 to 5%	Longitudinal slope of 7%
Surface hydrology	No water bodies in surrounding area. Hydrological network formed by a ravine known as Coro, situated at a distance of 1.1 km, flowing directly to the river Tocuyo (situated at 1.5 km)	No water bodies in surrounding area. Landfill situated upstream of hydrological network formed by ravines known as El Pauji (2.3 km) and El Roble (3.1 km). Both ravines are affluents of the river Morere, itself an affluent of the river Tocuyo. Intermittent ravines known as La Aragana and La Piedra situated at 1.8 and 2.2 km, respectively
Ground hydrology	Major aquifer presents water-table from 3 to 10 m, with wells of 40–60 m in depth and currents varying from 10 to 30 l/s	Local discontinuous aquifers
Seismic risk	Average acceleration: 230 gal (excedence probability 15%)	Average acceleration: 223 gal (excedence probability 15%)

Table 5 (*continued*)

Name	Guanarito	Chirico
Climate	Arid, extremely hot. Average annual precipitation: 297 mm; Average annual evaporation: 2250 mm; average annual temperature: 29 °C	Arid, hot. Average annual precipitation: 321 mm; average annual evaporation: 3521 mm; average annual temperature: 28 °C
Flora and Fauna	Predominance of shrub-like vegetation adapted to arid climates, characterized by spiked or thorny species with small leaves, particularly fleshy cacti. Fauna represented by miscellaneous groups of mixed and often nomadic species, continually on the move in response to changes in environmental conditions	Predominance of shrub-like vegetation adapted to arid climates, characterized by spiked or thorny species with small leaves, particularly fleshy cacti. Birds mostly granivorous or predators of insects and reptiles. Presence of frugal mammals, especially rabbit and fox. Terrestial reptiles belong to the lacertilian group, e.g. lizard and iguana, or to the ophidian group, e.g. the rattlesnake (genus *Crotalus*) and coral snake (genus *Micrurus*)
Soil uses	Uncultivated	Uncultivated
Infrastructure	Landfill located at 0.76 km from secondary road network, at 0.8 km from a bridge and at 2.2 km from water supply system (consisting of water tanks, well system and facilities for filling tanker trucks)	Landfill located at 0.5 from the 0017 artery road, at 1 km from a bridge and at 5.8 km from Carora airport
Distance from population points	Local hamlets Gaunarito and Mamón situated at 1.6 and 1.3 km, respectively, town of Siquisique situated at 2 km	Towns of Carora and Los Arenales situated at 5 and 3.5 km, respectively

The ERI for surface water obtained classifications of 'low' for the majority of deposit points, except for Los Palmares (3) and Guanarito (6), which were classified as average.

For groundwater, the ERI presented classifications of 'average' for all deposit points except Pavía (1) and Curva del Viento (4), which presented the minimum value of 0. However, the fact that a certain environmental element presents a null value for ERI should not be taken to mean that the element does not participate in the ecosystem; rather, it merely indicates that there is no interaction between the processes occurring in the deposit point and the relevant environmental element [4,9,29].

For atmosphere, the majority of deposit points presented a low ERI classification, with the exceptions of Pavía (1) and La Pica (7), which were classified as average and high, respectively. Similarly, most of the ERIs for soil were classified as low, except for Los Jebes (2) and Curva del Viento (4), which were classified as average. Finally, all ERIs for human health were high except for deposit point Pavía (1), which was average.

Table 9 shows statistical data for the indexes and for each environmental element. The environmental element with highest risk was human health, followed by groundwater, soil, atmosphere and finally surface water. Statistical analysis of the values obtained shows no statistically significant differences between the different deposit points ($p = 0.314$), but

Table 6
Description of La Pica deposit point

Name	La Pica
Superficie de vertido	4 ha
Composition of disponed waste	Mainly organic material, paper and cardboard. To a lesser extent glass and plastic
Geology	Soil characterized by terraced filling material consisting of sands, silt and gravel of recent origin
Geomorphology	Steep slopes of 30% approx.
Surface hydrology	Intermittent lagoon situated at 0.7 km. Ravine known as Agua Salada situated at 1 km
Ground hydrology	Presence of major aquifers with deposits exceeding 50 m in depth, formed mainly by permeable sand and gravel
Seismic risk	Mean acceleration 204 gal (excedence probability 15%)
Climate	Semi-arid, temperate. Average annual precipitation: 721 mm; average annual temperature: 24 °C
Flora and fauna	Vegetation typical of dry foothill woodland, including thicket and scrub. Presence of frugal mammals such as rabbit and fox. Terrestial reptiles belong to the lacertilian group, e.g. lizard and iguana, or to the ophidian group, e.g. the rattlesnake (genus *Crotalus*) and coral snake (genus *Micrurus*)
Soil uses	Urban
Infraestructura	Landfill located at 0.7 km from local road 03, and at 0.16 km from secondary road network. Drinking water storage tanks situated at 2.1 and 2.4 km. In addition, a well complex is situated at 2.7 km and a well used for urban supply at 1.1 km
Distance from population points	Neighbourhood known as Padre Oreni situated at 0.15 km; towns of Duaca and Eneal situated at 1 km and 0.55 km, respectively

Table 7
Priorities of landfills and environmental landfill interaction indexes in Estado Lara

Priorities	Deposit point	Environmental landfill interaction index (ELI)	
First	La Pica	7.67	Average
Second	Los Palmares	7.34	Average
Third	Guanarito	6.68	Average
Fourth	Los Jebes	6.37	Average
Fifth	Chirico	5.83	Average
Sixth	Curva del Viento	5.4	Average
Seventh	Pavía	3.74	Low

Table 8
Statistical data for the indexes

	N	Minimum	Maximum	Arithmetic mean	Standard deviation
ELI	7	3.74	7.67	6.13	1.33
ERI_i	35	0.00	2.58	1.23	0.69
eV_i	35	0.00	3.00	1.74	0.95
Pbc_i	35	0.38	0.94	0.69	0.13
Pbc_{o-i}	315	0.00	1.00	0.52	0.24
Pbc_{s-i}	112	0.00	1.00	0.44	0.33

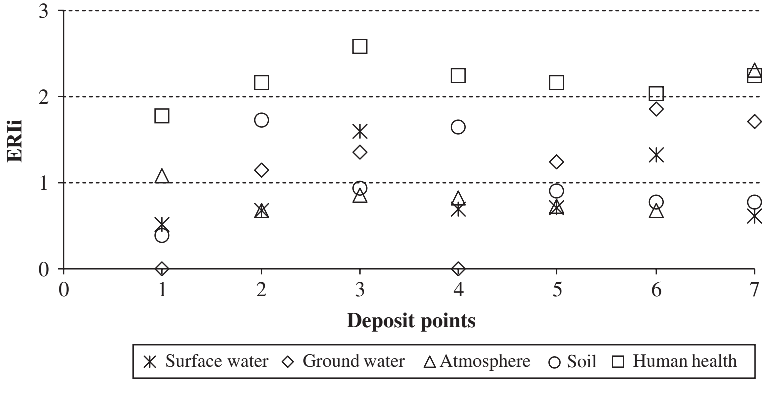


Fig. 3. Environmental risk index (ERI_i) for deposit points and each environmental element.

such differences do exist between environmental elements ($p = 0.001$). Using multiple comparison of data arranged by environmental elements, it was possible to distinguish between two groups. The first included the environmental element with highest ERI_i value, i.e. human health. The second group included the remaining environmental elements with lower values. The results confirmed the existence of sanitary problems in the deposit points and the inappropriate disposal of waste which poses a risk to health in the vast majority of landfills in Latin America and the Caribbean [3,4,6].

3.1.4. Environmental value

Fig. 4 shows environmental value for the different environmental elements for each deposit point in Estado Lara. Mean value for eV_i in the study area was 1.74 (Table 8), with maximum values of 3 presented by Guaranito (6) and La Pica (7) for groundwater and atmosphere, respectively. In the case of Pavía (1) and Curva del Viento (4), environmental value for groundwater was 0 due to the absence of groundwater near the deposit points (<1000 m) [31,34]. Maximum values of 3 were presented by all deposit points in the case of human health, as a result of the methodology definition.

Table 9 shows statistical data for the indexes and for each environmental element. After human health, the environmental element with highest environmental value was groundwater, followed by atmosphere, surface water and soil. Statistical analysis of

Table 9
Statistical data for indexes and each environmental element

Environmental element	Index	Arithmetic mean	Standard error	Confidence interval 95%	
				Upper limit	Lower limit
Surface water	ERI_i	0.87	0.41	1.60	0.51
	eV_i	1.29	0.49	2.00	1.00
	Pbc_i	0.67	0.09	0.80	0.51
Groundwater	ERI_i	1.04	0.76	1.86	0.00
	eV_i	1.71	1.25	3.00	0.00
	Pbc_i	0.58	0.08	0.68	0.41
Atmosphere	ERI_i	1.02	0.59	2.31	0.68
	eV_i	1.43	0.79	3.00	1.00
	Pbc_i	0.72	0.11	0.86	0.54
Soil	ERI_i	1.02	0.49	1.72	0.38
	eV_i	1.29	0.49	2.00	1.00
	Pbc_i	0.78	0.19	0.94	0.38
Human health	ERI_i	2.17	0.24	2.58	1.77
	eV_i	3.00	0.00	3.00	3.00
	Pbc_i	0.72	0.08	0.86	0.59

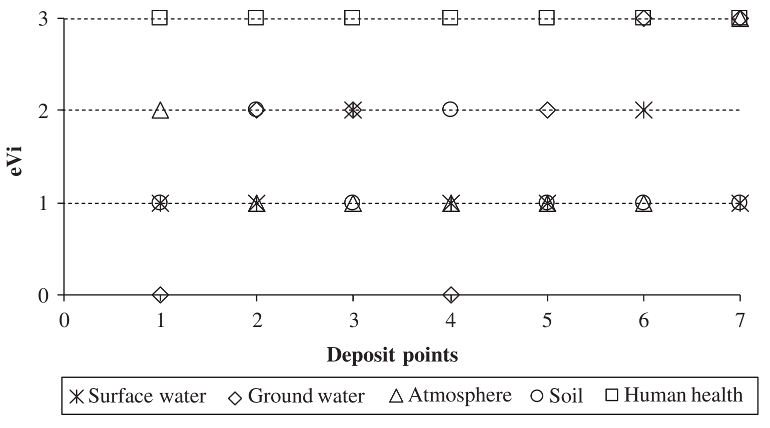


Fig. 4. Environmental value (eV_i) for deposit points and each environmental element.

values obtained shows no statistically significant differences between the different deposit points ($p = 0.575$), but such differences do exist between the environmental elements ($p = 0.001$). Using multiple comparison of data arranged by environmental elements, we again distinguished two groups, similar to those for ERI.

3.1.5. Probability of contamination

Fig. 5 shows probability of contamination for different environmental elements for each deposit point in Estado Lara. Mean value for Pbc_i in the study area was 0.69 (Table 8),

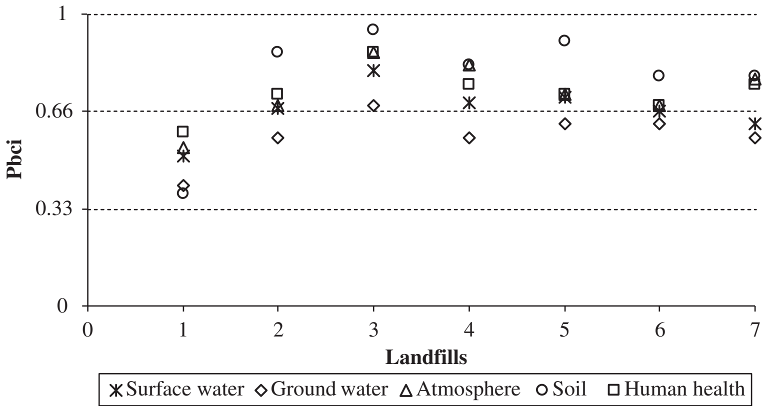


Fig. 5. Probability of contamination (Pbc_i) for deposit points and each environmental element.

with a maximum value of 0.94 presented by Los Palmares for the environmental element soil.

Probability of Contamination obtained values classified as average and high, due to the unsuitable sitting of the landfills and to their deficient operation. For surface water, Probability of Contamination was high in all cases except for Pavía (1) and La Pica (7). In all the landfills, groundwater presented an average Probability of Contamination except in the case of Los Palmares (3), where the value was high. Atmosphere presented a high Probability of Contamination in all landfills except Pavía (1). Likewise, the Probability of Contamination for soil and human health was high for all deposit points except Pavía (1), which was classified as average.

Table 9 shows statistical data for the indexes and for each environmental element. The environmental element with highest Probability of Contamination was soil, followed by human health, atmosphere, surface water and finally groundwater. Statistical analysis of Probability of Contamination obtained values showing statistically significant differences between the deposit points ($p = 0.000$), and similar differences also existed between environmental elements ($p = 0.001$). Multiple comparison of data arranged by deposit points made it possible to distinguish between two groups; the first included the deposit point Pavía (1), which presents lowest Probability of Contamination, while the remaining points pertained to the second group with higher Probability of Contamination. Using multiple comparison of data arranged by environmental elements, it was also possible to distinguish between two groups; the first included environmental elements with higher value (soil and health), while the second included the remaining environmental elements with lower Probability of Contamination.

Finally, analysis was undertaken of Contamination Probability values for the different variables grouped according to design and operation criteria and to landfill location (Pbc_{o-i}, Pbc_{s-i}). Mean probability values were higher for design and operation variables than for landfill location variables (Table 8). Statistically significant differences occur between variables related to operation and design as well as to location ($p = 0.010$). The most significant problems of municipal waste landfills in Estado Lara were shown to correspond to operation, although in most cases problems also derived from location [4,8,35].

4. Conclusions

The methodology applied to Estado Lara (Venezuela) for environmental diagnosis of municipal waste landfills provided sufficient data to determine the environmental threat posed by the landfills, although in order to take into account the specific legislation of this country it was necessary to make certain changes to the variables. Results were obtained for a series of environmental indexes which may be used as a basic tool for the study of appropriate deposit point location and to monitor their exploitation.

The high values for probability of contamination corresponding to different environmental elements reflect uncontrolled operating and design conditions and unsuitable location of deposit points throughout the area of study. Nevertheless, since environmental values for all the elements were not high, the environmental risk index produced classifications of low or average.

The methodology also constitutes a tool for the planning and prioritizing of action to be taken in different deposit points in particular areas. Application of the methodology in the area of study has led to a programme of action for future landfill investment, to be directed first at the improvement of exploitation of facilities and secondly to improvements in design, thus reducing the environmental impact. In the case of Pavía (ELI low), a Conditioning Plan is required to improve operation and design problems. In the remaining deposit points (ELI average), it will be necessary to study each index carefully to determine if a Conditioning Plan is sufficient or if a Sealing and Closing Plan is required owing to the unsuitable location of the deposit points. The Conditioning Plan or the Sealing and Closing Plan for each deposit point should involve a detailed study of the different variables analysed to obtain the Probability of Contamination for each environmental element. In the interest of brevity in the present article, such a detailed study will be the subject of two future papers.

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